Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in
Environmental Science & Health

The connectivity between soil erosion and sediment entrapment in reservoirs

Christiane Zarfl and Ana Lucía

Abstract

Rivers are characterized by their water flow regime and sediment transport. Sediments are crucial for channel morphology, water quality, providing habitat for aquatic organisms and, finally, for sustaining deltas. Rivers are, however, fragmented by dams and will face an additional building boom due to actions to mitigate climate change (with hydropower) and water scarcity. Reservoir siltation is a serious challenge for reservoir management but also entails downstream morphological impacts. However, sediment entrapment is an often neglected element in reservoir planning and environmental assessment. The aim of this study thus is to give an overview on the links between soil erosion and sediment entrapment in reservoirs, its degree on a global scale (reservoirs lose annually 1% of their capacity), the driving factors that influence associated processes and the different approaches for reservoir management to reduce siltation and its impacts downstream.

Addresses

Center for Applied Geoscience, Eberhard Karls Universität Tübingen, Hölderlinstraße, 12, 72074 Tübingen, Germany

Corresponding author: Zarfl, Christiane (christiane.zarfl@uni-tuebingen.de)

Current Opinion in Environmental Science & Health 2018, **5**:53–59

This review comes from a themed issue on **Sustainable soil management and land restoration**

Edited by **Paulo Pereira** and **Juan F. Martínez-Murillo**

For a complete overview see the Issue and the Editorial

https://doi.org/10.1016/j.coesh.2018.05.001

Keywords

Sediment transport, Land-use change, Reservoir capacity, Dams.

Introduction

Water availability in time is, and has been, technically fostered by storing water in reservoirs already millennia ago [1]. These reservoirs are mainly created by building a dam that stores the water that is draining from the upstream catchment. According to numbers of the current World Register of Dams, today more than 58,000 large dams (>15 m high or impounding more than 3 million m^3) store in total more than 16,000 km^3 of water globally [2]. But not only has water supply fostered dam construction. Global economic growth, an increasing electricity demand, and the need of reducing greenhouse gas emissions to curtail climate change promote an increasing search for renewable, “climate neutral” electricity sources. Currently, 22% of the global electricity production is provided by renewable sources, and 73% of these is covered by hydropower (data for 2014; [3]). In the future decades, we will most likely face an unprecedented boom in dam construction, with about 3700 major hydropower dams already in construction or in planning, especially in countries with emerging economies [4].

Despite the social benefits of dams and reservoirs, like water supply for drinking water or irrigation, renewable electricity production, energy storage, flood control, navigation and recreation, this technology comes along with severe social, economic and ecological effects, e.g. massive overrun of budget and time of construction [5,6], relocation of people and trans-boundary conflicts [7], increased prevalence of waterborne diseases [8], habitat degradation and threats to freshwater biodiversity [9–11], fragmentation of free-flowing rivers [12,13], and changes in the natural flow, thermal and sediment regime [14–16]. At the same time reservoirs may lead to the production of greenhouse gases, especially methane, when organic material trapped behind dams is degraded [17].

Dams do not only change the flow regime, fragment the river and disconnect its respective upstream and downstream reaches as well as its interaction with the floodplain [18,19], but also changes the sediment transport, affecting therefore two of the main controls of channel morphology [20]. They are very efficient retention features for sediments with an estimated global particle retention of 50% of the natural loads to the oceans [21]. Fluvial sediments depend on and, at the same time, define river morphology, transport nutrients to floodplains and form habitats for freshwater and riparian organisms. Sediments also play an important role as carriers for pollutants that sorb to the particles and are either transported with suspended particles or sink to bottom sediments. Lake sediments, for example, are used as “environmental archives” whose composition and contaminant concentrations mirror conditions and changes within catchment and atmospheric inputs over several years [22]. Those sediments result from in-stream erosion and subsequent advective transport but also from soil erosion within the catchment with mobilized particles that are transported and, in this way, connected to the river network. The

objective of this study thus is to support entangling this highly complex interaction of processes by outlining 1) the contribution of soil erosion and connectivity to the river channel to in-stream sediment transport, 2) the extent of sediment entrapment in reservoirs worldwide and its economic and ecologic meaning and 3) potential sediment management strategies that help to mitigate sediment entrapment.

Soil erosion and connectivity to the river channel

Fluvial sediment transport is the most effective transport process for eroded soils in terms of distance with soils/sediments from the catchment being transported more than 1 km [23]. With this, sediments within a river result from in-stream erosion processes or from soil eroded within the catchment and connected to the river channel.

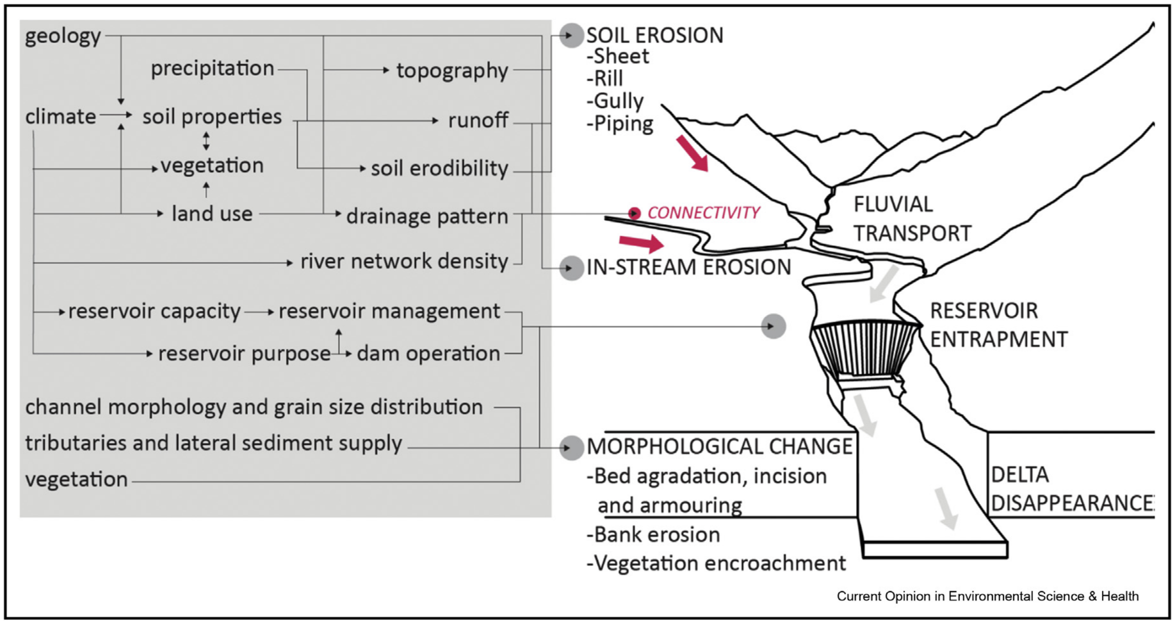
Soil erosion can either be of natural or anthropogenic origin. The first includes physical detachment processes induced by precipitation and runoff, avalanches or wind, but also biological activity, e.g. soil dwelling organisms. Different soil erosion processes have to be distinguished: sheet, rill and gully erosion, subsurface flow erosion (piping erosion), but also erosion due to tillage, land levelling (e.g. terracing for expanding cropland areas) or crop harvesting [23]. Human activities like agriculture, land levelling, mining and infrastructure construction accelerate erosion rates by orders of magnitude, Hooke et al. [24] estimated that in 2007 more than 50% of the ice-free land surface of the world have undergone transformations due to anthropogenic activities. Dearing et al. [25] for example showed by analysing European lake cores that deforestation in medieval times already increased natural soil erosion by up to a factor of one hundred. Also many other studies underline that soil erosion rates mainly increase by major land-use changes (e.g. Refs. [26,27]). Nevertheless, the factors controlling natural and human-induced erosion processes and the interactions between them are still scarcely understood. Topography with slope gradient and slope length plays an important role in determining soil loss rates but it strongly interacts with runoff and the hydrological response of the hillslope, e.g. in the case of sheet erosion [23]. Soils also hold an inherent susceptibility to erosion which depends on the soil properties and, in turn, on environmental conditions like climate [28]. Precipitation intensity disproportionately increases runoff and soil erosion which becomes especially relevant in times of climate change [29]. Panagos et al. [30], for example, predict a spatially highly variable increase in rain erosivity of 18% between 2010 and 2050 on a European scale. The influence of vegetation on soil erosion has mainly been investigated in relation to vegetation cover and canopy height, less with a focus on plant roots and their characteristics that might serve as a soil stabilizing factor [31,32]. Vegetation also plays a role in relation to impacts of land-use on soil erosion rates. Torri and Poesen [33] identified from 63 case studies on gully erosion worldwide that resistance to erosion strongly decreased from forest and grassland to rangeland and pasture and finally to cropland. Even more specific, soil erosion rates resulting from crop harvesting vary in dependence of crop type, soil properties including water content at time of harvest, tillage, harvesting practice and soil treatment afterward [34]. Reported soil loss rates related to harvesting of different types of crops (t ha^{-1} per harvest) and from countries all over the world compiled by Poesen [23] cover four orders of magnitude. Even more drastic human impacts on topography and soil erosion can be expected by land levelling activities like terracing or mountain levelling [35]. This results in a higher susceptibility of the freshly exposed soil to erosion and landslides [36]. In general, the different soil erosion processes and driving factors (Figure 1) need to be analysed in an integrated way since they might either accelerate or compensate each other when occurring at the same time. In order to upscale soil erosion rates measured at the plot scale several soil erosion models exist (e.g. Ref. [37]) that are of empirical or process-based origin.

But when and how do detached soils end up in the river to be transported downstream? While longitudinal connectivity describes the in-stream connectivity, lateral connectivity is the link of different hillslopes within a catchment to the river channel. Several conceptual framework exists that can be used to study this lateral connectivity [38–40], also with a special focus on human-impacted fluvial systems [41]. Again, topography and morphological complexity of a catchment play a crucial role in identifying potential erosion sites and subsequent sediment fluxes [42–44]. This includes river network density, soil type, surface roughness and vegetation structure [42,45], but also anthropogenic activities like land-use changes, like urbanization, that influence the natural drainage patterns [46]. Connectivity can be described with field based observations [47]and by measuring sediment fluxes in the field [48]. Indices and GIS (Geographic Information System)-based modelling approaches have been developed and combined with field measurements to quantify the potential connectivity within a watershed [42,43,49] and within the fluvial network [47,50]. Combining soil erosion and connectivity gives an idea of soil/sediment delivery within the river network. This is followed by in-stream sediment transport further downstream – potentially entrapped behind dams.

Sediment entrapment in reservoirs

Sediments result from soil erosion and in-stream sediment transport, they accumulate within the reservoir and may substantially reduce the life span of a reservoir

Figure 1

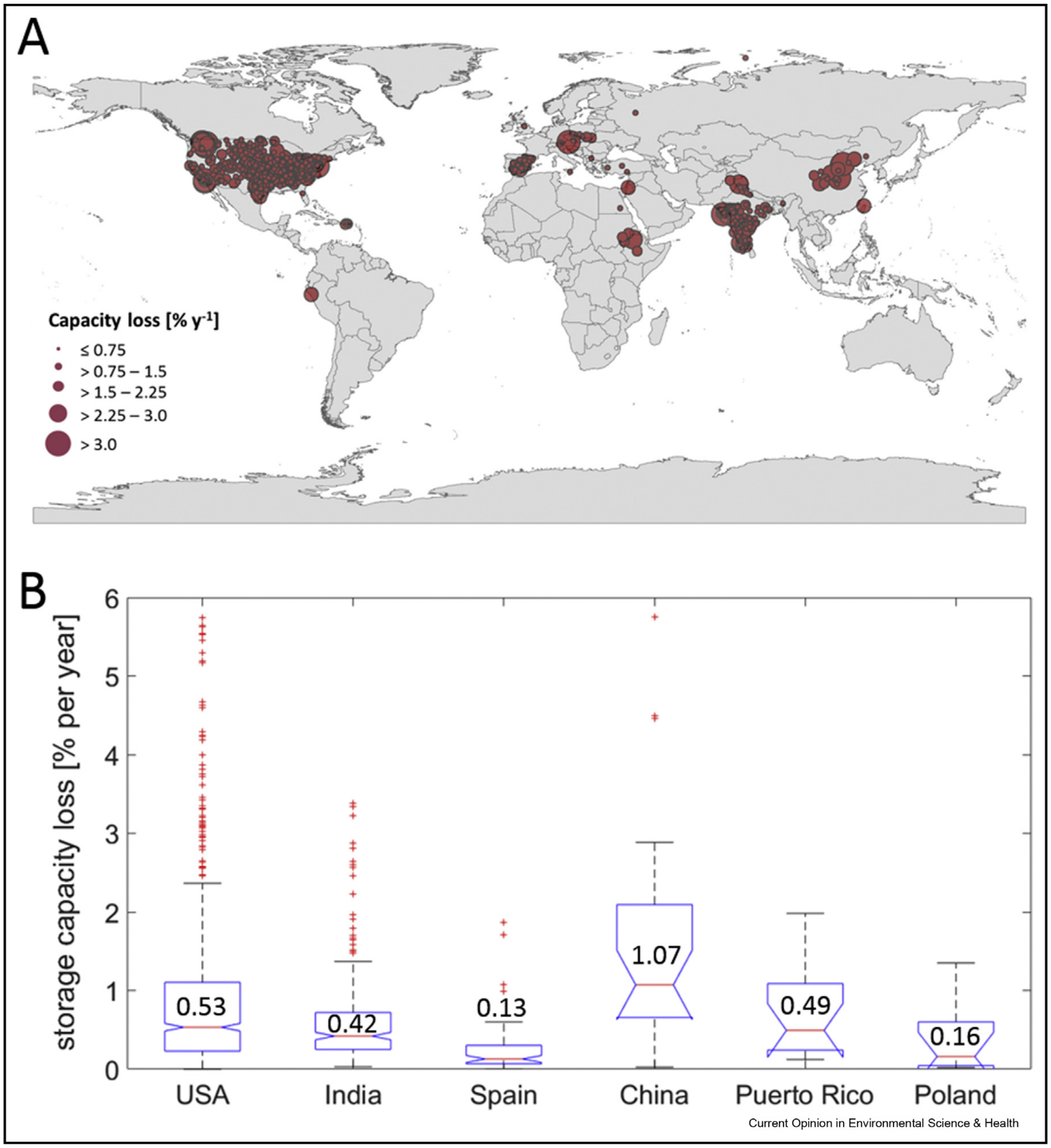


Conceptual figure on the link between soil erosion and sediment entrapment in reservoirs and their influencing factors. Bold red and grey arrows indicate sediment mobilization and fluxes, respectively, light black arrows represent interactions with and in between control parameters. Effects back to climate (e.g. from land use) have been neglected for clarity reasons. Details are described in the text.

causing major economic consequences by decreasing the storage capacity. Due to sedimentation, many large reservoirs in the US that had originally been designed for up to 200 years experienced a reduction in lifetime by 50–100 years [51]. Therefore, additional costs are associated with dredging the reservoir and removing sediments. In addition, so-called “sediment-starved” water or “hungry water” released from the reservoir causes downstream bank erosion, channel incision, floodplain disconnection [20,52], but also infrastructure damage [53].

Existing reservoirs worldwide constructed since the 1960s have accumulated over 100 billion metric tons of sediment, greatly reducing sediment loads [54]. Recent model calculations for cumulative trapping of sediments by dams on the Mekong River show that only 4% of the total sediment load could be expected to reach the river delta [55]. River deltas, however, populated by half a billion people, depend on river-borne sediments to prevent coastal erosion and increased salt water intrusion [56,57]. Due to missing sediment supply and sea level rise the Mekong delta is predicted to disappear by the end of the century [58]. Another study, using observed siltation data in more than 1200 reservoirs (1024 from USA, 191 worldwide) for evaluation, estimated the loss in reservoir capacity due to sedimentation on a global scale and based on the Global Reservoir and Dams database (GRanD [59]) to currently amount to 5% in relation to the installed capacity [60]. This estimated number is also influenced by reservoir age. Sediment entrapment is, nevertheless, very site specific and controlled by dam operation but also environmental conditions as described above in relation to soil erosion and connectivity. In order to quantify this variability in more detail, we thus exemplarily collected monitoring data on annual capacity loss rates ($m^3\ y^{-1}$) due to siltation for 1124 existing reservoirs worldwide, with data availability dominated by publications for the USA (806) and India (241), but increasing representatively of the worldwide data with respect to the work of Wisser et al. [60]. The average capacity loss per year worldwide is 0.9%. However, it ranges up to on average 2.5% per year in China (27 data points). The majority (95%) of the collected data is below 3% storage capacity loss. Still, the variability among the data is quite high (Figure 2, Figure S1) and is a consequence of the complexity of sediment origins including soil erosion, its connectivity to the river channel, in-stream erosion, and fluvial sediment transport but also reservoir operation. More details on the collected data can be found in the SI (Table S1). Sediment entrapment represents a loss to water storage and thus water quantity, but reservoir sediments also represent sinks for contaminants [61]. Pollutants from the catchment, especially hydrophobic substances, sorb to and are transported with particles which settle in the reservoir due to reduced flow velocities. This can, on the one hand, imply improved water quality in downstream and coastal regions [62]. On the other hand, the contaminated

Figure 2



A. Location of reservoirs with exemplarily compiled reservoir capacity loss data (n = 1193) due to sediment entrapment. Size of symbols indicates % loss of storage capacity per year. Details for the USA and India are exemplarily given in the Supporting Information (Figure S1). B. Annual reservoir storage capacity loss (%) as monitored in different countries (with n > 5). Numbers represent the median of each dataset. For clarity reasons, outliers for the USA >6% (up to 14.3%) and one outlier for China (30%) are not shown here but are included in the data evaluation. Note that the number of underlying compiled data differs: USA: 806; India: 239; Spain: 69; China: 26; Puerto Rico: 15; Poland: 8.

sediments may act as a long-term source of pollution. Changes in discharge, sediment remobilization, water chemistry, and climate lead to the release of accumulated pollutants into the water column and thus represent a hidden toxicological risk to biodiversity and ecosystem services [63] as well as to the human population, which depends on the stored water for drinking or irrigation purposes.

In the near future, the role of reservoirs in sediment entrapment will further increase not only due to the future boom in dam construction (that will mainly occur in countries of the Global South) but also due to climate and major land-use changes. This will induce increased soil erosion loadings of pollutants and nutrients [64] and change lateral connectivity while additional dam construction, due to its character as a barrier, will decrease

the longitudinal connectivity in the river channel. It is therefore crucial to continue research on understanding the processes leading to soil erosion, its connectivity to the river channel, sediment accumulation in reservoirs but also downstream morphological changes. These changes can range from bed incision, armouring and aggradation to bank erosion, vegetation encroachment and delta disappearance (Figure 1) [65–67]. Knowledge and data on these processes can help selecting dam locations more carefully and soil and reservoir management can be adjusted to increase the life span of reservoirs and minimize morphological changes downstream.

Sediment management in relation to reservoirs

Awareness for the need for managing sediment in reservoirs is given and also spread on an international level, e.g. by the International Hydropower Association who, in December 2017, launched a knowledge hub on successful sediment management to extend the lifetime of reservoirs [68]. Different options exist to tackle and avoid reservoir siltation: 1) reduction of sediment input including the decrease of upstream soil and channel erosion and sediment trapping upstream of the reservoir (precautionary action); 2) passing sediment around or through the reservoir by maintaining sediment transport and reducing its deposition (attendant action); and 3) excavating sediments or flushing sediments by adopting dam operation (correcting action) [55]. These actions require specific knowledge on and data for quantifying the processes that influence sediment entrapment, but also the ones that are impacted by these specific actions to improve their development and evaluation. Thus, sediment entrapment in reservoirs is not only an issue of reservoir capacity. As outlined above, aquatic and riparian ecosystems strongly depend on natural sediment regimes [69]. Many processes that determine channel morphology and river bed heterogeneity, water quality, habitat structure and dynamics are sediment-related. Thus, management strategies like bypassing sediments, especially in case of already existing dams, do not only have the opportunity to reduce siltation rates within the reservoir but also to provide sediments to river reaches downstream of the dam and thus to mitigate sediment starvation while keeping up the sediment supply to delta regions even though these sediments might carry pollutants from the upstream catchment. For example, Kondolf et al. [53] showed that threats to the Mekong delta can only be understood in the context of the connected functions of the river system. Moreover, a practice that can also be taken into account is dam removal. This has become increasingly popular in the past few decades, especially in the USA, and is often related to the raising awareness of fragmentation impacts on fish populations. Dam removal is often an option in case of outdated dams where maintenance or environmental costs outweigh the benefits or in risk of failure of the dam. Dam removal leads to a sudden sediment and potentially also contaminant release which also affects ecosystems and morphology of rivers that seem to be quite resilient [70]. For dams to be built, construction sites should be selected carefully and related to soil and sediment erosion of their potential catchment. This requires the application of (available) mathematical models that spatially estimate soil erosion rates, connectivity of the detached soils to the fluvial network and integration with estimations on in-stream erosion processes and fluvial sediment transport.

In summary, sediment entrapment in reservoirs already plays an important economic and ecologic role worldwide, it results from processes that have an integrated character on a catchment scale (e.g. soil erosion, laterally connected transport to the river channel) and it will become an even more discussed issue with additional dam building activities that disturb longitudinal connectivity within the river channel. This finally underlines the urgent need for a sediment management approach that mitigates siltation in (potentially cascading) reservoirs and that considers land-use and climate change impacts on a catchment scale and even across boundaries. Development of a common policy between actors and stakeholders that agree on joined objectives, strategies and timeframes [71] will be challenging but crucial if reservoir management shall be sustainable with reduced economic, ecologic and social burdens to future generations [72].

Conflict of interest statement

Nothing declared.

Acknowledgements

This study has been funded by the Excellence Initiative of the German Federal Ministry of Education and Research (BMBF) and the German Research Foundation (DFG) at the University of Tübingen as well as by the Ministry of Science, Research and the Arts of the State of Baden-Württemberg, Germany. We thank Martin Luccarelli for his support in the design of the conceptual figure (Figure 1). We also thank Klaus Röhler and Behrend Dellwisch for support in collecting spatial data on sediment entrapment in reservoirs worldwide and creation of the respective map (Figure 2A). Finally, we thank the two anonymous reviewers for their comments that helped to improve the manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.coesh.2018.05.001

References

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest
** of outstanding interest

1. Bravard JP: **Les barrages dans l'histoire: Géographie des foyers d'innovation et des influences technologiques**. 2002, **4–5**:130–133.

2. *ICOLD International commission on large dams: world register of dams*. 2018. Available online, http://www.icold-cigb.net/.

3. The World Bank. 2018. Available online: http://databank.worldbank.org/.

4. Zarfl C, Lumsdon AE, Berlekamp J, Tydecks L, Tockner K: **A global boom in hydropower dam construction**. *Aquat Sci* 2015, **77**:161–170.

5. Ansar A, Flyvbjerg B, Budzier A, Lunn D: **Should we build more large dams? The actual costs of hydropower megaproject development**. *Energy Pol* 2014, **69**:43–56.

6. Flyvbjerg B: **What you should know about megaprojects and why: an overview**. *Proj Manage J* 2014, **45**:6–19.

7. Richter BD, Postel S, Revenga C, Lehner B, Churchill A: **Lost in development's shadow: the downstream human consequences of dams**. *Water Altern* 2010, **3**:14–42.

8. Lerer LB, Scudder T: **Health impacts of large dams**. *Environ Impact Assess Rev* 1999, **19**:113–123.

9. Poff NL: **Rivers of the anthropocene?** *Front Ecol Environ* 2014, **12**. 427–427.

10. ** Winemiller KO, McIntyre PB, Castello L, Fluet-Chouinard E, Giarrizzo T, Nam S, Baird IG, Darwall W, Lujan NK, Harrison I, *et al.*: **Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong**. *Science* 2016, **351**:128–129.
This study illustrates the potential impacts of dams on aquatic biodiversity with a focus on fish species in especially species rich river systems.

11. Auerbach DA, Deisenroth DB, McShane RR, McCluney KE, Poff NL: **Beyond the concrete: accounting for ecosystem services from free-flowing rivers**. *Ecosyst Serv* 2014, **10**:1–5.

12. Nilsson C, Reidy CA, Dynesius M, Revenga C: **Fragmentation and flow regulation of the world's large river systems**. *Science* 2005, **308**:405–408.

13. Grill G, Lehner B, Lumsdon AE, MacDonald GK, Zarfl C, Liermann CR: **An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales**. *Environ Res Lett* 2015, **10**. 015001.

14. Constantine JA, Dunne T, Ahmed J, Legleiter C, Lazarus ED: **Sediment supply as a driver of river meandering and floodplain evolution in the Amazon Basin**. *Nat Geosci* 2014, **7**: 899–903.

15. * Piqué G, Batalla RJ, López R, Sabater S: **The fluvial sediment budget of a dammed river (upper Muga, southern Pyrenees)**. *Geomorphology* 2017, **293**:211–226.
This article presents results of a 3-year study on the sediment budget of a mediterranean dammed river showing that >95% of the upstream sediments were trapped within the reservoir, and indicating a shift to suspended sediments transported downstream of the dam.

16. ** Schleiss AJ, Franca MJ, Juez C, De Cesare G: **Reservoir sedimentation**. *J Hydraul Res* 2016, **54**:595–614.
This vision paper gives an overview on processes contributing to reservoir sedimentation, management approaches and development of measurement techniques.

17. Maeck A, DelSontro T, McGinnis DF, Fischer H, Flury S, Schmidt M, Fietzek P, Lorke A: **Sediment trapping by dams creates methane emission hot spots**. *Environ Sci Technol* 2013, **47**:8130–8137.

18. Biemans H, Haddeland I, Kabat P, Ludwig F, Hutjes RWA, Heinke J, von Bloh W, Gerten D: **Impact of reservoirs on river discharge and irrigation water supply during the 20th century**. *Water Resour Res* 2011, **47**:15.

19. Döll P, Fiedler K, Zhang J: **Global-scale analysis of river flow alterations due to water withdrawals and reservoirs**. *Hydrol Earth Syst Sci* 2009, **13**:2413–2432.

20. Grant GE: **The geomorphic response of gravel-bed rivers to dams: perspectives and prospects**. In *Gravel-bed rivers*, vols. 165–181. John Wiley & Sons, Ltd; 2012, https://doi.org/10.1002/9781119952497.ch15.

21. Vörösmarty CJ, Meybeck M, Fekete B, Sharma K, Green P, Syvitski JPM: **Anthropogenic sediment retention: major global impact from registered river impoundments**. *Global Planet Change* 2003, **39**:169–190.

22. Smol JP: *Pollution of lakes and rivers: a paleoenvironmental perspective*. 2nd edn. Malden MA: John Wiley & Sons; 2008.

23. ** Poesen J: **Soil erosion in the anthropocene: research needs**. *Earth Surf Process Landforms* 2018, **43**:64–84.
This is an excellent detailed overview on soil processes, driving factors and potential future development.

24. Hooke RL, Martín Duque JF, Pedraza J: **Land transformations by humans: a review**. *GSA Today* 2012, **22**:4–10.

25. Dearing JA: **Climate-human-environment interactions: resolving our past**. *Clim Past* 2006, **2**:187–203.

26. Montgomery DR: **Soil erosion and agricultural sustainability**. *P Natl Acad Sci* 2007, **104**:13268–13272.

27. * Vanwalleghem T, Gómez JA, Infante Amate J, González de Molina M, Vanderlinden K, Guzmán G, Laguna A, Giráldez JV: **Impact of historical land use and soil management change on soil erosion and agricultural sustainability during the Anthropocene**. *Anthropocene* 2017, **17**:13–29.
This manuscript elucidates the historical and current developments related to land-use and its impacts on soil erosion.

28. Sanchis MPS, Torri D, Borselli L, Poesen J: **Climate effects on soil erodibility**. *Earth Surf Process Landforms* 2008, **33**: 1082–1097.

29. Nearing M, Pruski FF, O'Neal MR: **Expected climate change impacts on soil erosion rates: a review**. *J Soil Water Conserv* 2004, **59**:43–50.

30. Panagos P, Ballabio C, Meusburger K, Spinoni J, Alewell C, Borrelli P: **Towards estimates of future rainfall erosivity in Europe based on REDES and WorldClim datasets**. *J Hydrol* 2017, **548**:251–262.

31. Bardgett RD, Mommer L, De Vries FT: **Going underground: root traits as drivers of ecosystem processes**. *Trends Ecol Evol* 2014, **29**:692–699.

32. Vannoppen W, De Baets S, Keeble J, Dong Y, Poesen J: **How do root and soil characteristics affect the erosion-reducing potential of plant species?** *Ecol Eng* 2017, **109**:186–195.

33. Torri D, Poesen J: **A review of topographic threshold conditions for gully head development in different environments**. *Earth Sci Rev* 2014, **130**:73–85.

34. Ruysschaert G, Poesen J, Verstraeten G, Govers G: **Soil loss due to crop harvesting: significance and determining factors**. *Prog Phys Geogr* 2004, **28**:467–501.

35. Li P, Qian H, Wu J: **Accelerate research on land creation**. *Nature* 2014, **510**:29–31.

36. Borselli L, Torri D, Øygarden L, De Alba S, Martínez-Casasnovas JA, Bazzoffi P, Jakab G: **Land levelling**. In *Soil erosion in Europe*, vols. 643–658. John Wiley & Sons, Ltd; 2006, https://doi.org/10.1002/0470859202.ch46.

37. de Vente J, Poesen J, Verstraeten G, Govers G, Vanmaercke M, Van Rompaey A, Arabkhedri M, Boix-Fayos C: **Predicting soil erosion and sediment yield at regional scales: where do we stand?** *Earth Sci Rev* 2013, **127**:16–29.

38. Poeppl RE, Parsons AJ: **The geomorphic cell: a basis for studying connectivity**. *Earth Surf Process Landforms* 2018, https://doi.org/10.1002/esp.4300.

39. Fryirs KA, Brierley GJ, Preston NJ, Kasai M: **Buffers, barriers and blankets: the (dis)connectivity of catchment-scale sediment cascades**. *Catena* 2007, **70**:49–67.

40. Bracken LJ, Turnbull L, Wainwright J, Bogaart P: **Sediment connectivity: a framework for understanding sediment transfer at multiple scales** 2015, **40**:177–188.

41. * Poeppl RE, Keesstra SD, Maroulis J: **A conceptual connectivity framework for understanding geomorphic change in human-impacted fluvial systems**. *Geomorphology* 2017, **277**:237–250.

The novelty of this study is to explicitely link the change in geomorphic connectivity of fluvial systems to human behaviour, especially to feedback loops in landuse change.

42. Borselli L, Cassi P, Torri D: **Prolegomena to sediment and flow connectivity in the landscape: a GIS and field numerical assessment**. *Catena* 2008, **75**:268–277.

43. Cavalli M, Trevisani S, Comiti F, Marchi L: **Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments**. *Geomorphology* 2013, **188**:31–41.

44. Persichillo MG, Bordoni M, Cavalli M, Crema S, Meisina C: **The role of human activities on sediment connectivity of shallow landslides**. *Catena* 2018, **160**:261–274.

45. Foerster S, Wilczok C, Brosinsky A, Segl K: **Assessment of sediment connectivity from vegetation cover and topography using remotely sensed data in a dryland catchment in the Spanish Pyrenees**. *J Soils Sediments* 2014, **14**:1982–2000.

46. Tarolli P, Sofia G: **Human topographic signatures and derived geomorphic processes across landscapes**. *Geomorphology* 2016, **255**:140–161.

47. * Wohl E, Rathburn S, Chignell S, Garrett K, Laurel D, Livers B, Patton A, Records R, Richards M, Schook DM, *et al.*: **Mapping longitudinal stream connectivity in the North St. Vrain Creek watershed of Colorado**. *Geomorphology* 2017, **277**:171–181.
The authors show with their comprehensive analysis that stream gradient derived from digital elevation models is the most robust indicator of relative longitudinal connectivity within the river network compared to further potential control variables, e.g. upland vegetation, hydroclimatology, or road crossings.

48. Comiti F, Marchi L, Macconi P, Arattano M, Bertoldi G, Borga M, Brardinoni F, Cavalli M, D'Agostino V, Penna D, *et al.*: **A new monitoring station for debris flows in the European Alps: first observations in the Gadria basin**. *Nat Hazards* 2014, **73**: 1175–1198.

49. Cavalli M, Tarolli P, Dalla Fontana G, Marchi L: **multi-temporal analysis of sediment source areas and sediment connectivity in the Rio Cordon catchment (Dolomites)**. *Rend Online Soc Geol Ital* 2016, https://doi.org/10.3301/ROL.2016.39.:27-30.

50. Schmitt RJP, Bizzi S, Castelletti A: **Tracking multiple sediment cascades at the river network scale identifies controls and emerging patterns of sediment connectivity**. *Water Resour Res* 2016, **52**:3941–3965.

51. Hargrove WL, Johnson D, Snethen D, Middendorf J: **From dust bowl to mud bowl: sedimentation, conservation measures, and the future of reservoirs**. *J Soil Water Conserv* 2010, **65**: 14A–17A.

52. Kondolf GM: **PROFILE: hungry water: effects of dams and gravel mining on river channels**. *Environ Manag* 1997, **21**: 533–551.

53. ** Kondolf GM, Schmitt RJP, Carling P, Darby S, Arias M, Bizzi S, Castelletti A, Cochrane TA, Gibson S, Kummu M, *et al.*: **Changing sediment budget of the Mekong: cumulative threats and management strategies for a large river basin**. *Sci Total Environ* 2018, **625**:114–134.
The study exemplarily illustrates with the case of the Mekong River how delta regions are threatened by cumulating effets from the whole river network, highlighting the importance of undisturbed sediment transport.

54. Syvitski JPM, Vörösmarty CJ, Kettner AJ, Green P: **Impact of humans on the flux of terrestrial sediment to the global coastal ocean**. *Science* 2005, **308**:376–380.

55. Kondolf GM, Gao Y, Annandale GW, Morris GL, Jiang E, Zhang J, Cao Y, Carling P, Fu K, Guo Q, *et al.*: **Sustainable sediment management in reservoirs and regulated rivers: experiences from five continents**. *Earth's Future* 2014, **2**:256–280.

56. Syvitski JPM, Kettner AJ, Overeem I, Hutton EWH, Hannon MT, Brakenridge GR, Day J, Vörösmarty C, Saito Y, Giosan L, *et al.*: **Sinking deltas due to human activities**. *Nat Geosci* 2009, **2**: 681.

57. Evans G: **Deltas: the fertile dustbins of the continents**. *Proc Geologists' Assoc* 2012, **123**:397–418.

58. Schmitt RJP, Rubin Z, Kondolf GM: **Losing ground – scenarios of land loss as consequence of shifting sediment budgets in the Mekong Delta**. *Geomorphology* 2017, **294**:58–69.

59. Lehner B, Reidy Liermann C, Revenga C, Vorosmarty C, Fekete B, Crouzet P, Doll P, Endejan M, Frenken K, Magome J, *et al.*: **High-resolution mapping of the World's reservoirs and dams for sustainable river-flow management**. *Front Ecol Environ* 2011, **9**:494–502.

60. Wisser D, Frolking S, Hagen S, Bierkens MFP: **Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs**. *Water Resour Res* 2013, **49**:5732–5739.

61. Shotbolt LA, Thomas AD, Hutchinson SM: **The use of reservoir sediments as environmental archives of catchment inputs and atmospheric pollution**. *Prog Phys Geogr* 2005, **29**: 337–361.

62. Urbaniak M, Kiedrzyńska E, Zieliński M, Tołoczko W, Zalewski M: **Spatial distribution and reduction of PCDD/PCDF Toxic Equivalents along three shallow lowland reservoirs**. *Environ Sci Pollut Res Int* 2014, **21**:4441–4452.

63. Fanny C, Virginie A, Jean-François F, Jonathan B, Marie-Claude R, Simon D: **Benthic indicators of sediment quality associated with run-of-river reservoirs**. *Hydrobiologia* 2013, **703**:149–164.

64. Lambin EF, Meyfroidt P: **Global land use change, economic globalization, and the looming land scarcity**. *Sci Total Environ* 2011, **108**:3465–3472.

65. Grant GE, Schmidt JC, Lewis SL: **A geological framework for interpreting downstream effects of dams on rivers**. In *A peculiar river*. Edited by O'Connor JE, Grant GE; 2013, https://doi.org/10.1029/007WS13.

66. Scorpio V, Aucelli PPC, Giano SI, Pisano L, Robustelli G, Rosskopf CM, Schiattarella M: **River channel adjustments in Southern Italy over the past 150 years and implications for channel recovery**. *Geomorphology* 2015, **251**:77–90.

67. Guillén J, Palanques A: **A historical perspective of the morphological evolution in the lower Ebro river**. *Environ Geol* 1997, **30**:174–180.

68. IHA International Hydropower Association: Sediment management hub. 2017. Available online, https://www.hydropower.org/sediment-management.

69. Wohl E, Bledsoe BP, Jacobson RB, Poff NL, Rathburn SL, Walters DM, Wilcox AC: **The natural sediment regime in rivers: broadening the foundation for ecosystem management**. *Bioscience* 2015, **65**:358–371.

70. Major JJ, East AE, O'Connor JE, Grant GE, Wilcox AC, Magirl CS, Collins MJ, Tullos DD: **Geomorphic responses to dam removal in the United States – a two-decade perspective**. In *Gravel-bed rivers*, vols. 355–383. John Wiley & Sons, Ltd; 2017, https://doi.org/10.1002/9781118971437.ch13.

71. Giardino A, Schrijvershof R, Nederhoff CM, de Vroeg H, Brière C, Tonnon PK, Caires S, Walstra DJ, Sosa J, van Verseveld W, *et al.*: **A quantitative assessment of human interventions and climate change on the West African sediment budget**. *Ocean Coast Manag* 2017, https://doi.org/10.1016/j.ocecoaman.2017.11.008.

72. * George MW, Hotchkiss RH, Huffaker R: **Reservoir sustainability and sediment management**. *J Water Resour Plann Manag* 2017, **143**. 04016077.
This study investigates costs and benefits of reservoir projects and underlines how to improve the sustainability and life span of reservoirs, e.g. by including infrastructure damage into cost-benefit-analysis.